PAVEMENT CAUSED FOD TO AIRCRAFT ENGINES

M.C. Hironaka
MAR, Incorporated
hironakamc@nfesc.navy.mil

C. J. Schiavino
Naval Facilities Engineering Service Center
schiavinocj@nfesc.navy.mil

G.D. Cline
Naval Facilities Engineering Service Center
gregory.d.cline@navy.mil

ABSTRACT

The Naval Facilities Engineering Service Center conducted a study on the cause of the damage to aircraft engines that are operated by the Navy and Marine Corps. The objective of the investigation was to determine what portion of the damaged engines was caused by pavement material as FOD (Foreign Object Debris). Data for this study were obtained from "Engine FOD Incident Reports" that were prepared by aircraft operators for each engine damaged by FOD during the period January 1997 to April 2003. Each report is prepared as required by Chief of Naval Operations Instruction OPNAVINST 4790.2H and includes findings from the inspection of the damaged engine. The reports include (1) description of the damage, (2) analysis for the cause of the damage, (3) actual FOD ingested (if known), and (4) suspected FOD if actual is unknown. In order to determine what percent of the damage was caused by pavement material, it was required to collect the data for the entire engine damage "global population" of data. Each reported incident was analyzed and placed in one of twelve categories. The categories with the major amount of FOD incidences include (1) aircraft originated hardware/fasteners, (2) carrier deck occurrences, (3) rock and pebbles, (4) other metallic objects, (5) birds, (6) unknown (but not likely rock) and (7) airborne refueling accidents. Pavement material was responsible for the least amount of incidences (0.4%) of the damaged engines.

INTRODUCTION

Objective

The objective of this study was to determine what percentage of the aircraft engines damaged by "Foreign Object Debris" (FOD) was caused by asphalt or concrete pavement fragments or joint seal material. This information will provide needed data in determining if pavement condition levels as measured by the Pavement Condition Index (PCI) should be tightened to a higher level to reduce the probability of pavement material being the source of FOD that cause damage to aircraft engines.

Background

This study is based on data obtained from Engine FOD Incident Reports, which are prepared by all Navy and Marine Corps operators of jet aircraft whose engines have been damaged by FOD. These reports must be written as required by the Chief of Naval Operations (CNO) as specified in OPNAVINST4790.2H. Each engine that is damaged by FOD is documented in detail in these reports. Included in these reports is specific information on:

- Aircraft – type, model, series, and bureau number
- Engine – type, model, series, serial number, and installed position on the aircraft
- Julian date when the engine was damaged by FOD
- Julian date and type of last maintenance and repair

- Location of the aircraft when the engine was damaged by FOD
- Cost data
- Investigative Results - Evidence, analysis of evidence, identification of actual FOD, if possible, or suspected object and material if actual is not identifiable.
- Corrective action to prevent recurrence
- Commanding Officer's comments

Copies of the generated reports are submitted to the cognizant headquarters command of the aircraft operators as well as to the CNO, Commander Naval Air Systems Command (NAVAIR), and the Navy Safety Center.

Identifying Causes of FOD Damage

There are some guidelines for FOD identification and investigation in aircraft maintenance instruction manuals. However, skill in being proficient at identifying the cause is gained primarily through hands-on experience investigating damaged engines. In the investigations, the damage characteristics of the engine and components are studied. Some examples of revealing characteristics are that the damage occurred:

1. Only in one or several blades in the front section
2. Only in the mid to aft section
3. Throughout the engine

The damage characteristics above suggests the following, respectively:

1. The cause could be rock, ice, or pavement since the object was friable (i.e., broke up upon impact)
2. An internal failure occurred
3. A metallic object caused the damage because the object was not friable

There are positive visual and analytical methods for determining the actual FOD that caused the damage. An example of a telltale visual positive sign of the actual FOD is blood and feathers. If feathers are retrieved, an expert on birds can even identify the species. An analytical method is described in Reference [1]. In that method, residue samples are taken from the damaged engine blade and analyzed by various methods to identify the material of the FOD that impacted the blade. By knowing the material components, the object that caused the damage can be deduced and positively identified.

Some examples of FOD caused damage are shown in Figures 1 through 6. These photographs are courtesy of NAVAIR and Failure Analysis Service Technology (FAST). Although FAST provided photographs are of commercial aircraft engines, they illustrate the type of damage that occurs when various types of FOD (e.g., fasteners, concrete, tool, and ice) are ingested into an engine. The FOD itself can cause serious damage to an engine as can be seen in these photographs. If the FOD causes a piece of a blade or the blade itself to be liberated, the damage is compounded.

DATA SOURCES

After describing the purpose of this investigation and receiving authorization to review archived FOD reports, reports from the following organizations were reviewed:

- Naval Air Force, US Pacific Fleet, San Diego
- Naval Air Force, US Atlantic Fleet, Norfolk
- Strike Fighter Wing US Pacific Fleet, Lemoore
- Strike Fighter Wing US Atlantic Fleet, Oceana
- Third Marine Aircraft Wing, Miramar
- Naval Air Station, Whidbey Island

Reports were either obtained in hard copy or electronic media format and reviewed at the Naval Facilities Engineering Service Center (NFESC) or reviewed on site. The following data were extracted from the reports and input into Excel files for analysis:

- Date of Damage to Engine by FOD
- Aircraft Type

- Engine Type and Serial Number
- Standard Cost to Repair
- Location of Aircraft when Damage Occurred
- Identity of the FOD

After reviewing over a thousand reports and culling duplicates of the same report that were present from the multiple sources, the data from a total of 843 reports were retained for review and analysis.

As FOD caused engine damage occurs over time, the Engine FOD Incident Reports that are generated may be available through the following Major Claimants under which aircraft are operated:

- Commander, U.S. Atlantic Fleet
- Commander, U.S. Pacific Fleet
- Commander, U.S. Naval Forces Europe
- Commander, Naval Education and Training
- Commander, Naval Reserve Force
- Commander, Naval Air Systems Command
- Commandant of the Marine Corps

In this investigation, all available reports from Commander, U.S. Atlantic Fleet and Commander, U.S. Pacific Fleet available through Commander, Naval Air Atlantic Fleet (COMNAVAIRLANT) and Commander, Naval Air Pacific Fleet (COMNAVAIRPAC) offices respectively, were reviewed. Reports that were available at these two Major Commands also included reports from the Marine Corps. Hence, this study was conducted on essentially 100% of the data available from these three Major Commands. It is possible that some of the 843 reports reviewed may have included documents for engines being operated by one or more of the other listed Major Commands. Such damage by FOD could occur while that aircraft was visiting an airfield of one of the three Major Commands mentioned above. In any event, it could be stated that this is a comprehensive study of the engine data available from those three Major Commands.

ENGINE DAMAGE CAUSE CATEGORIES

Each FOD incident report was studied to extract the cause of the engine damage. The emphasis of the review was to weigh whether pavement material was responsible for the damage. Hence, the categories established for the cause of the damage reflect this emphasis. Each report was studied for the cause of the damage and assigned to one of the following categories:

- Aircraft - Airborne Refueling Related
- Aircraft - Metallic Object
- Aircraft - Nonmetallic Object
- Birds
- Debris - Nonmetallic
- Ground Support Equipment
- Ice
- Maintenance Tools and Supplies
- Metallic - Unknown Source
- Pavement Material
- Personal Items
- Rocks
- Ship Deck - Unknown Source
- Unknown - Not Rock
- Unknown - Truly

The following categories require some clarification:

- Aircraft - Airborne Refueling Related (e.g., parts and pieces from refueling system from either aircraft)
- Aircraft - Metallic Object (e.g., fasteners, dislodged hardware, fragments)
- Aircraft - Nonmetallic Object (e.g., tire pieces, insulation, light lens fragments)
- Debris - Nonmetallic (e.g., wood, plastic caps)

- Metallic - Unknown Source (Evidence indicates damage caused by metal but source is not identifiable)
- Pavement Material - Asphalt and concrete pavement fragments and joint seals
- Rock - Material that is friable and causes less damage than metallic objects
- Ship Deck - Unknown Source - This category is assigned if the engine damage occurred aboard ship and the cause cannot be assigned to one of the other categories.
- Unknown - Not Rock (Based on the damage characteristics, this category is used when rock is likely not the cause, for example, when only the high power section is damaged.)
- Unknown - Truly (This category is assigned when evidence and description of cause is lacking or the cause could not be determined based on the evidence or lack thereof.)

In general, the assigning of each FOD caused incident to one of the above categories was straightforward. The degree of difficulty in determining the category to assign each incident ranged from simple to "truly unknown" based on the information included in the report. The following are examples of simple assignments because the actual objects that caused the damage was identified and in some cases recovered:

- Flat Head Machine Screw (Part Number: MS 24694-S3)
- Start Bleed Valve Nut (Part Number: MS 21043-06)
- Door Three Fastener (Part Number: 192014-6K-8)

Other reports that are intermediate in nature as to the reliability of the stated cause include "suspected" object. These include parts of the aircraft that are missing forward of the intake of the engine that was damaged or from the evidence at the damage site. Examples of these include:

- Rubber residue
- Glass pieces (e.g., embedded in nose gear tire)
- Metal fragments

DATA ANALYSES

The data analysis followed a simple procedure. All of the data was first inputted into Excel worksheets. Worksheets were first developed for the respective data from COMNAVAIRLANT and COMNAVAIRPAC, which also included the data for the Marine Corps. The following analyses were performed on the data:

- COMNAVAIRLANT Distribution of FOD Damage Causes
- COMNAVAIRPAC Distribution of FOD Damage Causes
- Common Time Frame of January 2002 to March 2003
- All Available Data (January 1997 to April 2003) Combined
- Rock and Pavement Material as FOD by Location and Aircraft Type

Separate analyses were performed on the data for each worksheet developed. The worksheets were then combined to extract the data for the common time frame between the data for the two Major Claimants of January 2002 to March 2003. The reason for selecting this time frame is that the data from Commander, Naval Air Force, U.S. Atlantic Fleet was limited to this time frame.

The original worksheets were combined a second time to perform an analysis of <u>all</u> the collected data regardless of the time frame. It should be noted that the combined database that includes all of the collected data might not be entirely representative of the FOD damage experience of the three Major Claimants mentioned above. This is because the data is incomplete for the years prior to January 2002 for these Major Claimants. Only data for the aircraft that were operated by the following Wing Commands for the stated time period is included in the analysis:

- Strike Fighter Wing Pacific - January 1997 to March 2003
- Strike Fighter Wing Atlantic - June 2000 to March 2003
- Third Marine Air Wing - January 1999 to March 2003

So the data is incomplete for two reasons: (a) the beginning time period of the data is different and (b) aircraft not operated by the Wings above but within the purview of the Major Commands are not included.

Finally, the combined database for all of the data was used to evaluate the portion of the damaged engines that were caused by rock and pavement material. The results of all of the analyses are summarized in the Tables 1 through 7 and Figures 7 through 10.

DISCUSSION

Comprehensiveness of Collected FOD Data

To develop an overall view of the comprehensiveness of the data contained in this study, the 843 collected reports will be compared with the total number of engines being operated by the three Major Commands from which the reports were obtained. The following assumptions will be made to facilitate this comparison:

- Each aircraft has two engines
- Total Number of Aircraft being operated (from Global Security.org websites):
  - 1,400 COMNAVAIRLANT
  - 1,600 COMNAVAIRPAC
  - ____ Marine Corps (number not readily available)

With the values presented above, the overall percent of operating engines damaged by FOD is calculated to be:

(843 / 6,000) x 100 = 14%

Similarly, the percent of operating engines damaged by rock and pavement material are, respectively:

(59 / 6,000) x 100 = 1%
(3 / 6,000) x 100 = 0.05%

If the number of aircraft being operated by the Marine Corps is included, the overall percentages will be less. So, it could be stated that less than 14% of all operating engines are damaged by all types of FOD and less than 1% and 0.05% are caused by rocks and pavement material, respectively.

Results of FOD Data Analyses

The results of the various analyses conducted are presented in Tables 1 through 6 and Figures 7 through 10. Various analyses were conducted because of the different time periods that the collected data from the different sources encompassed. The data was first analyzed separately disregarding the time frame for each set of data. The results of this analysis are shown in Figures 7 and 8, which present the data from COMNAVAIRLANT and COMNAVAIRPAC, respectively. Note in these figures that metallic objects from the aircraft itself or of unknown origin comprise a large percentage of the cause of the damaged engines. Also note that pavement material is responsible for only a very small percentage (<0.4%) of the damaged engines.

The results of the analyses incorporating the data over the common time frame of January 2002 through March 2003 are shown in Table 1 and summarized in Figure 9. In Table 1, it can be seen that metallic objects originating from the aircraft itself is the cause of a large portion of the FOD incidences. The second leading cause of engine damage is by FOD ingested while on shipboard, where pavement debris is not present. Figure 9 shows a comparison between the FOD incidences experienced by aircraft operators in COMNAVAIRLANT and COMNAVAIRPAC activities during this common time period. It can be seen in this figure that the distribution of the causes could be considered statistically the same for both Commands. One difference worthy of note is "rocks" where COMNAVAIRPAC activities experienced twice as much as COMNAVAIRLANT activities. This difference is discussed in further detail later in this paper.

The results of the analyses incorporating all of the data collected are shown in Table 2 and Figure 10. In Table 2, it can be seen that metallic objects are responsible for 44% of the damaged engines. There is a good possibility that metal objects could also be involved in the damaged engines assigned to the categories of "Ship deck – Unknown Source" and "Unknown - Not Rock." The category of "Rocks" was responsible for 7% of the damaged engines and "Pavement Material" for 0.4%.

Cost of FOD Damage by Rock and Pavement

The results of the analyses for rock and pavement caused damage are shown in Tables 3 through 6. Table 3 is a detail listing of each FOD incident caused by rock material. Some FOD Incident Reports did not include an entry for repair cost. To facilitate development of a cost estimate for engine repairs due to rock damage, cost figures for those incidences that lacked an entry, which are denoted with an asterisk (*) in the table, were extracted from the data for the respective aircraft and engine type. Entered in this table are the "mode" values respectively for the data for each aircraft and engine type. The data set from which each mode value was selected was formed by first considering the Standard Reportable Costs prescribed by the Navy Safety Center in Reference [2], which also instructs that the labor cost to remove and replace the engines should be added to obtain the total costs. Those cost values that did not include the labor and those costs for replacement with a new engine (vice repair) were excluded in the data set for determining the mode value. By using these costs and the costs contained in the FOD reports for the other incidences, the total cost for all the 59 FOD incidences caused by rock was estimated to be $8,015,000. Needless to say this is a significant amount of dollars to expend for repairing damaged engines.

The result of the analysis for pavement caused damage is shown in Table 4. As indicated in the previous paragraph, the costs denoted with an asterisk (*) are the "mode" values of the costs in the selected data set for the respective aircraft and engine type. By using these costs, the total cost for all three FOD incidences caused by pavement was estimated to be $226,000. Although this figure is less than that caused by rocks and the other causes, it is still an amount that should receive consideration. The pavement fragments that caused the damage could have originated from deteriorated pavements that are raveling or spalling or from construction debris. Since it cannot be determined from the existing information where the pavement fragments that caused the damage originated from, it would be prudent at this time to not alter (raise or lower) but retain the standard minimum Pavement Condition Index (PCI) values being used for Navy and Marine Corps airfield pavements.

Engine Height versus FOD Incidences

The collected data for engine damage by rocks was used to assess if any correlation exists between aircraft engine intake height above the ground surface and frequency of FOD occurrence. The data for rocks was used because these are the objects that are most likely to be present on the pavement surface and could be thrust upward by the nose gear of the aircraft or become airborne due to jet blast from leading aircraft. Based on the collected data as shown in Table 6 for rock caused incidences, it is not possible to determine if the occurrence of engine damage can be correlated with the height of the aircraft engine intake above the ground surface. A cursory review of the data suggests that there could be a weak (but unreliable) correlation in some of the data. For example, if the data for F/A-18 Models A, B, C, and D (same intake height) is compared with that of the P-3C (i.e., 20 incidences versus 2, respectively) one could conclude that height was a factor. However, other very important factors such as number of operating aircraft of each type, frequency of takeoffs and landings of those aircraft, flight hours, abundance of rock as potential FOD, and severity of wind conditions have not been accounted for in that cursory example.

However, the data in Table 5 suggests that there is a correlation between rock-caused FOD damage and Station location. This correlation is apparent in that table where it can be seen that the air stations, mostly in the western United States where there are little to no vegetation or other stabilizing agents in the infield areas, have the most rock caused damage. In these areas, rocks can migrate to the pavement surface by jet blast, strong winds, and vehicles. If the infield areas were stabilized, this would minimize rocks originating from those areas.

Stabilizing Infield Areas

Depending on the soil type present in the infield areas, different methods of stabilization should be applied. Site-specific conditions, which include weather factors and onsite maintenance capabilities, will have to be considered to develop a site-specific design. In considering alternative designs for a specific site, other factors, such as abundance of birds should be incorporated. For example, if grass is selected, birds tend to congregate in these areas to feed and as can be seen in the tables and charts presented earlier, birds are significant contributors to occurrence of FOD damage. This discussion focuses on stabilizing loose sand and gravel as can be found at the air stations discussed above where the most rock caused engine damage occurred. Methods that are considered to be cost prohibitive or require very high maintenance were excluded. Considering the type of soil at those stations, suitable stabilization methods are presented in Table 7. The method most suitable for use depends on whether or not fine soil material is present along with the sand and gravel. The methods included in Table 7 can be implemented with limited labor skills and inexpensive materials.

FINDINGS

1. For the period January 2002 through March 2003, the following are the findings from the analysis of the COMNAVAIRLANT and COMNAVAIRPAC FOD data.

   a. Summary of causes of the FOD incidences that occurred during January 2002 through March 2003:

Summary of Causes	Number of Incidences	Percent (%)
Metallic - Aircraft Parts & Unknown Origin	119 & 46	40.5
Ship deck & In-flight Refueling Occurrences	58 & 15	17.9
Unknown - Not Rock or Truly Unknown	46 & 23	17.0
Birds	29	7.1
Rocks	22	5.4
Nonmetallic - Aircraft Parts	10	2.5
Ice	8	2.0
Other - Debris, Tools, Miscellaneous	17, 11, & 3	7.6
Pavements	0	0
Total:	407	100

   b. Objects originating from the aircraft, ship decks, in-flight refueling equipment, and unknown sources cause the majority of the damage to engines by FOD.

   c. There were no FOD incidences caused by pavement material during this period.

2. For ***all*** of the collected data regardless of the time frame, the following are the findings from the analysis of the COMNAVAIRLANT and COMNAVAIRPAC FOD data.

   a. Summary of causes of the FOD incidences for all collected data:

Summary of Causes	Number of Incidences	Percent (%)
Metallic - Aircraft Parts & Unknown Origin	262 & 109	44.0
Ship deck & In-flight Refueling Occurrences	104 & 23	15.1
Unknown - Not Rock or Truly Unknown	79 & 53	15.6
Birds	57	6.8
Rocks	59	7.0
Nonmetallic - Aircraft Parts	29	3.4
Ice	18	2.1
Other - Debris, Tools, Miscellaneous	22, 21, & 4	5.6
Pavements	3	0.4
Total:	843	100.0

   b. Objects originating from the aircraft, ship decks, in-flight refueling equipment, and unknown sources cause the majority of the damage to engines by FOD.

d. There were only three FOD incidences that were caused by pavement material and thus it can be stated that pavement material was responsible for only 0.4% of the 843 incidences studied. The cost to repair the three engines is calculated to be $226,000.

e. There were 59 incidences caused by rocks, which represents 7% of the 843 incidences studied. The cost to repair the 59 engines is calculated to be $8,015,000.

f. The occurrence of engine damage by rocks is more prevalent at the air stations located in the arid western United States where infield areas have little to no vegetation or other stabilizing agents.

g. There is insufficient data to determine if a correlation exists between engine height above the pavement surface and occurrence of engine damage by FOD.

h. Total number of FOD incidences for COMNAVAIRLANT and COMNAVAIRPAC combined has been reduced as exemplified by the following data:

June 1979 through December 1980:	1,143 Incidences/19 Months	~ 60/month	[3]
January 2002 through March 2003:	407 Incidences/15 Months	~ 27/month	

CONCLUSIONS

1. Pavement material is responsible for less than 0.4% of the engines damaged by FOD.

2. Conscientious efforts of aircraft operating squadron personnel aboard carriers and air stations to prevent FOD incidences have been substantially productive as evidenced by the reduction in the rate of FOD damaged engines.

3. Based on the findings from this study, a change in the threshold levels for the Pavement Condition Index (PCI) for the various airfield pavement areas should be retained at the present levels as specified previously by the Naval Facilities Engineering Command (NAVFAC).

RECOMMENDATIONS

1. The threshold levels for PCI for the various airfield pavement areas and the frequency of surveys continue to be used without any modifications.

2. To reduce the probability of rocks being potential FOD:
   a. Insure that all airfield pavement areas that require shoulders meet requirements of Reference [4] and are kept in good condition.
   b. Stabilize infield areas where rocks can originate due to jet blast and wind.

3. Continue FOD prevention programs.

4. Investigate the use of the more powerful regenerative air runway sweepers that meet Air Force requirements for airfield pavement use [5].

ACKNOWLEDGMENT

The following persons provided information and FOD reports or facilitated access to those reports and therefore were instrumental to the success of this study:

LT Florencio Arceo
LCDR Nora Burghardt
GYSGT Michael Caplinger
AD1 Rick Carroll
Lloyd Jardine
Clayton Kemmerer
AE1 Angela Langston
AVCM Dale McComsey

Vern Cooper
LCDR John Farwell
ADCS Patrick Guris
SSGT Jon Henderson
George Morse
LT Tom Murphy
ADC Brian Tourville

REFERENCES

1. Failure Analysis Service Technology. Technical Brochure. Pine Mountain, California, Undated.

2. Navy Safety Center. Message R 071430Z Mar 02, 2002 Engine Cost Data for Aviation Mishap Reporting.

3. Naval Postgraduate School. Masters Thesis: Foreign Object Damage in Naval Aircraft Engines, by Jack B. Mills. Monterey, California, June 1981.

4. Unified Facilities Criteria. UFC 3-260-01: Airfield and Heliport Planning and Design, 10 November 2001.

5. Air Force Purchase Description: WR-ALC/TRA 3825-093A, Cleaner Vacuum/Air Self Propelled.

LIST OF TABLES

LIST OF FIGURES

TABLE 1 FOD Incidents for Period January 2002 through March 2003

Cause	COMNAVAIRLANT Number Incidents	COMNAVAIRPAC Number Incidents	Total Incidents	Percent (%)
Aircraft Metallic Object	62	57	119	29.2
Ship Deck - Unknown Source	34	24	58	14.3
Metallic - Unknown Source	23	23	46	11.3
Unknown - Not Rock	28	18	46	11.3
Birds	19	10	29	7.1
Unknown - Truly	16	7	23	5.7
Rocks	7	15	22	5.4
Debris - Nonmetallic	9	8	17	4.2
Aircraft In-flight Refueling Related	7	8	15	3.7
Maintenance Tools & Supplies	8	3	11	2.7
Aircraft Nonmetallic Object	7	3	10	2.5
Ice	5	3	8	2.0
Personal Items	1	1	2	0.5
Ground Support Equipment	1	0	1	0.2
Pavement Material	0	0	0	0.0
Totals:	**227**	**180**	**407**	**100.0**

TABLE 2 Summary of FOD Incidents for All Collected Data

Description of Cause	Number of Incidents	Percent (%)
Aircraft Metallic Objects	262	31.1
Metallic - Unknown Source	109	12.9
Ship Deck - Unknown Source	104	12.3
Unknown - Not Rock	79	9.4
Rocks	59	7.0
Birds	57	6.8
Unknown - Truly	53	6.3
Aircraft Nonmetallic Objects	29	3.4
Aircraft In-flight Refueling Related	23	2.7
Debris - Nonmetallic	22	2.6
Maintenance Tools & Supplies	21	2.5
Ice	18	2.1
Pavement Material	3	0.4
Personal Items	2	0.2
Ground Support Equipment	1	0.1
Water	1	0.1
Total	**843**	**100**

TABLE 3 Rock Caused FOD Incidents by Location, Aircraft Type, and Cost (For all Collected Data)

Location of Aircraft When FOD Ingested	Aircraft Type	Engine Type	Cost ($)
Deployed - Operation Enduring Freedom	AV-8B	F402-RR-408A	289,480
Diego Garcia	P-3C	T56-A-14	110,990
Diego Garcia	P-3C	T56-A-14	110,990
Fresno Airport	F/A-18C	F404-GE-400	75,239*
HMT-303	UH-1N	T400-CP-400	17,397
In-flight near Salton Sea	SH-60F	T700-GE-401C	50,721
Martins State Air National Guard Base	AV-8B II+	F402-RR-408A	289,480
MCAGCC 29 Palms	AH-1W	T700-GE-401C	496,643
MCAGCC 29 Palms	AV-8B	F402-RR-408A	289,480
MCAGCC 29 Palms	KC-130T	T56-A-16	22,493
MCAS Camp Pendleton	CH-46E	T58-GE-16	68,798*
MCAS Miramar	CH-46E	T58-GE-16	68,798*
MCAS Miramar	CH-46E	T58-GE-16	68,798*
MCAS Miramar	CH-46E	T58-GE-16	68,798*
MCAS Miramar	CH-53E	T64-GE-416	88,402*
MCAS Miramar	CH-53E	T64-GE-416	88,402*
MCAS Miramar	CH-53E	T64-GE-416A	84,528*
MCAS Miramar	CH-53E	T64-GE-416	88,402*
MCAS Miramar	F/A-18C	F404-GE-402	75,239*
MCAS Miramar	F/A-18D	F404-GE-402	75,239*
MCAS Miramar	KC-130F	T56-A-16	67,167*
MCAS Miramar	UH-1N	T400-CP-400	18,875
MCAS New River	CH-46E	T58-GE-16	68,798
MCAS New River	CH-46E	T58-GE-16	1,106
MCAS Yuma	AV-8B	F402-RR-406B	1,666,666
MCAS Yuma	AV-8B	F402-RR-408A	172,000
MCAS Yuma	CH-46E	T58-GE-16	68,798
MCAS Yuma	UH-1N	T400-CP-400	18,865
NAF El Centro	F/A-18C	F404-GE-402	80,023
NAF El Centro	F-14B	F110-GE-400	256,308

*The report for these FOD Incidences did not include a cost so the "mode" value of the data for each aircraft and engine type was used.

TABLE 3 Rock Caused FOD Incidents by Location, Aircraft Type, and Cost (Continued) (For all Collected Data)

Location of Aircraft When FOD Ingested	Aircraft Type	Engine Type	Cost ($)
NAF Key West	F-14A	TF30-P-414A	112,484
NAS Fallon	F/A-18A	F404-GE-400	41,723
NAS Fallon	F/A-18A	F404-GE-400	26,430
NAS Fallon	F/A-18A	F404-GE-400	25,942
NAS Fallon	F/A-18C	F404-GE-400	1,576,800
NAS Fallon	F/A-18C	F404-GE-400	75,239
NAS Fallon	F/A-18C	F404-GE-400	75,239
NAS Lemoore	F/A-18B	F404-GE-400	41,723
NAS Lemoore	F/A-18C	F404-GE-400	80,888
NAS Lemoore	F/A-18C	F404-GE-400	80,888
NAS Lemoore	F/A-18C	F404-GE-400	75,239*
NAS Lemoore	F/A-18C	F404-GE-400	75,239
NAS Lemoore	F/A-18C	F404-GE-400	75,239
NAS Lemoore	F/A-18C	F404-GE-400	75,239*
NAS Lemoore	F/A-18C	F404-GE-402	83,922
NAS Lemoore	F/A-18C	F404-GE-400	132,413
NAS Lemoore	F/A-18E	F414-GE-400	900
NAS Lemoore	F/A-18E	F414-GE-400	26,380*
NAS Lemoore	F/A-18E	F414-GE-400	3,211
NAS Lemoore	F/A-18F	F414-GE-400	26,380
NAS Lemoore	F/A-18F	F414-GE-400	26,380
NAS Lemoore	F/A-18F	F414-GE-400	26,380
NAS Norfolk	CH-46E	T58-GE-16	68,798*
NAS North Island	S-3B	TF34-GE-400B	4,819
NAS North Island	S-3B	TF34-GE-400B	551
NAS North Island	SH-60B	T700-GE-401C	27,980
NAWS China Lake	F/A-18D	F404-GE-400	5,542
OLF Imperial Beach	SH-60B	T700-GE-401C	27,980
Unknown	AV-8B	F402-RR-406B	168,230
Total Incidences	**59**		**$8,015,101**

*The report for these FOD Incidences did not include a cost so the "mode" value of the data for each aircraft and engine type was used.

TABLE 4 Pavement Caused FOD Incidents by Location, Aircraft Type, and Cost (For all Collected Data)

Location of Aircraft When FOD Ingested	Aircraft Type	Engine Type	Cost ($)
NAS Fallon	F/A-18B	F404-GE-400	75,239*
NAS Fallon	F/A-18C	F404-GE-402	75,239*
MCAS Miramar	F/A-18C	F404-GE-402	75,239*
Total Incidences	**3**		**$225,717**

* The report for these FOD Incidences did not include a cost so the "mode" value of the data for each aircraft and engine type was used.

TABLE 5 Rock and Pavement Caused FOD Incidents at Various Air Stations and Aircraft Types (For all Collected Data)

Station	Rock Caused FOD	Number Incidences of Aircraft Types	Pavement Caused FOD	Number Incidences of Aircraft Types
NAS Lemoore	15	1- F/A-18B 8- F/A-18C 3- F/A-18E 3- F/A-18F		
MCAS Miramar	11	1- F/A-18C 1- F/A-18D 1- KC-130F 3- CH-46E 4- CH53E 1- UH-1N	1	1- F/A-18C
NAS Fallon	6	3- F/A-18A 3- F/A-18C	2	1- F/A-18C 1- F/A18B
MCAS Yuma	4	1- CH-46E 1- UH-1N 2- AV-8B		
MCAGCC 29 Palms	3	1- AH-1W 1- AV-8B 1- KC-130T		
NAS North Island	3	2- S-3B 1- SH-60B		
Diego Garcia	2	2 - P-3C		
MCAS New River	2	2 - CH-46E		
NAF El Centro	2	1- F/A-18C 1- F-14B		
Deployed-Operation Enduring Freedom	1	1- AV-8B		
Fresno Airport	1	1- F/A-18C		
HMT-303	1	1- UH-1N		
In-flight near Salton Sea	1	1- SH-60F		
Martins State Air National Guard Base	1	1- AV-8B II+		
MCAS Camp Pendleton	1	1- CH-46E		
NAF Key West	1	1- F-14A		
NAS Norfolk	1	1- CH-46E		
NAWS China Lake	1	1- F/A-18D		
OLF Imperial Beach	1	1- SH-60B		
Unknown	1	1- AV-8B		
Total Incidences	59		3	

TABLE 6 Number of Rock Caused FOD Incidences by Aircraft Type (For all Collected Data)

Aircraft Type	Number of Incidences
F/A-18C	14
Ch-46E	8
AV-8B	5
CH-53E	4
F/A-18A	3
F/A-18E	3
F/A-18F	3
UH-1N	3
F/A-18D	2
P-3C	2
S-3B	2
SH-60B	2
AH-1W	1
AV-8B II+	1
F/A-18B	1
F-14A	1
F-14B	1
KC-130F	1
KC-130T	1
SH-60F	1
Total	59

TABLE 7 Methods to Stabilize Airfield Infield Areas

Soil Type & Conditions	Stabilization Method
Sand and Gravel without Fines **(*USCS Type: GW and GP)** • **Without fine material** • **Loose with little moisture** • **No Traffic Usage** • **Subjected to Jet Blast** • **Subjected to High Winds**	**<u>Soil Stabilizer</u>** ***Types:*** Organic and Inorganic Stabilizers (The organic type allows permeation of moisture thereby minimizing ponding of water.) ***Application:*** Both types are mixed into the upper 3 to 4 inches of soil, mixture is thoroughly wetted and compacted typically with a power roller (1,000 lbs). ***Durability:*** Soil binders last approximately 6 years with minimal maintenance. ***Comments:*** This type of stabilization method is probably the most expensive method due to the associated equipment and manpower required for installation. However many suppliers are available and best cost is usually obtained from local venders. **<u>Soil Reinforcement Mat</u>** ***Types:*** Surface Mats of Synthetic Permanent Material ***Application:*** The mats are available in rolls ranging in widths from 4 to 10 feet and lengths up to 200 feet. The typical installation involves rolling the mat onto the prepared surface and anchoring the edges of the membrane in 2-foot deep trenches. The installation of staples ranging in length from 6 to 12 inches may also be used to secure mats to the ground. ***Durability:*** Reinforcement mats should provide permanent protection and complete erosion protection from initial installation. If the mat is torn, it can be repaired easily. ***Comments:*** Permanent reinforcement mats have typically been utilized for drainage channel surfaces (unvegetated) to provide erosion protection. When selecting the product to use, the mats with low elongation properties and high shear stress resistance should be selected. Additional research is recommended for use along airfield pavements to determine the ability of synthetic mats to withstand jet blast and high winds. A combination of permanent mats used in conjunction with a surface penetrant (cutback or emulsified asphalt) has proven effective in other applications. The cost for soil reinforcement mats is lower than the soil stabilizer option previously discussed primarily due to labor cost.

TABLE 7 Methods to Stabilize Airfield Infield Areas (Continued)

Soil Type & Conditions	Stabilization Method
Sand and Gravel with fines **(*USCS Type: GW and GP)**	**<u>Vegetative</u>** ***Types:*** Drought tolerant grasses or low growing ground covers that are indigenous to the specific site. ***Application:*** Hydro seeding, mechanical seeding, and sprigging. ***Durability:*** Durability is good if installed properly as witnessed by many highway plantings throughout the country. Most critical is proper plant selection. ***Comments:*** It is recommended that native grasses and plant materials be used when possible as they are sustainable and have proven adaptable to the local climatic conditions. Ground covers are more labor intensive but when used in conjunction with native grasses can provide a suitable cover that is self-sustaining and can endure dry soil conditions. Given suitable soil conditions this method will provide a suitable remedy for mitigating FOD at a very reasonable cost with good durability and limited maintenance. Cost of this method is lower than the previously discussed options.

***Unified Soil Classification System**

FIGURE 1 Example of a FOD damaged jet engine blade. (Courtesy of NAVAIR)

FIGURE 2 Suspected cause of damage is circular shaped object. (Courtesy of NAVAIR)

FIGURE 3 Example of damage caused by a fastener. (Courtesy of F.A.S.T.)

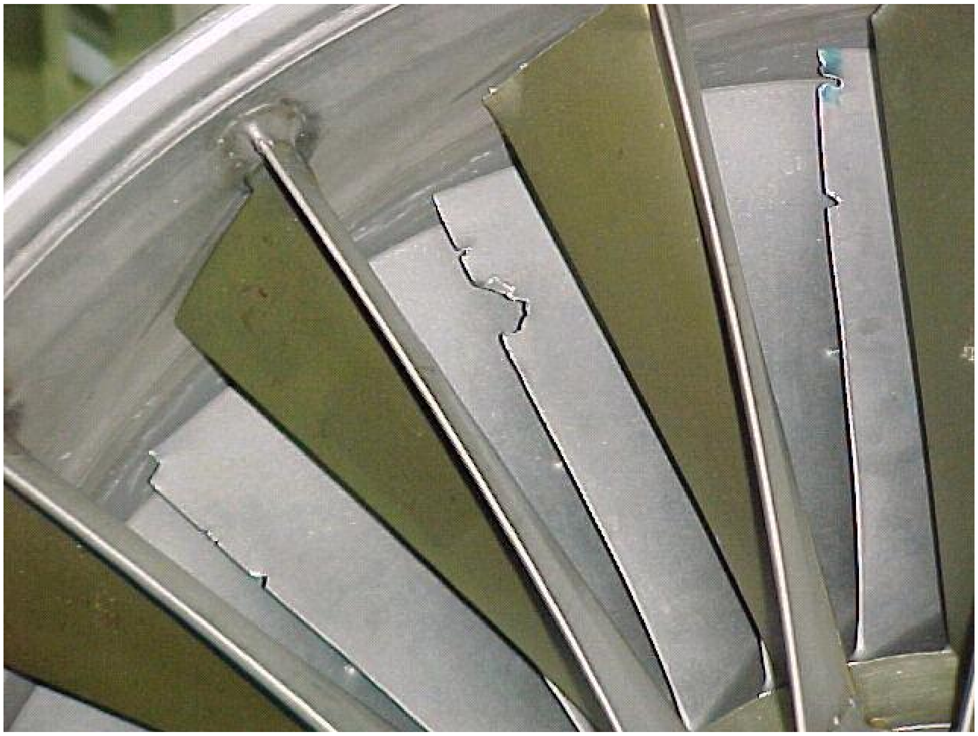

FIGURE 4 Example of damage caused by concrete. (Courtesy of F.A.S.T.)

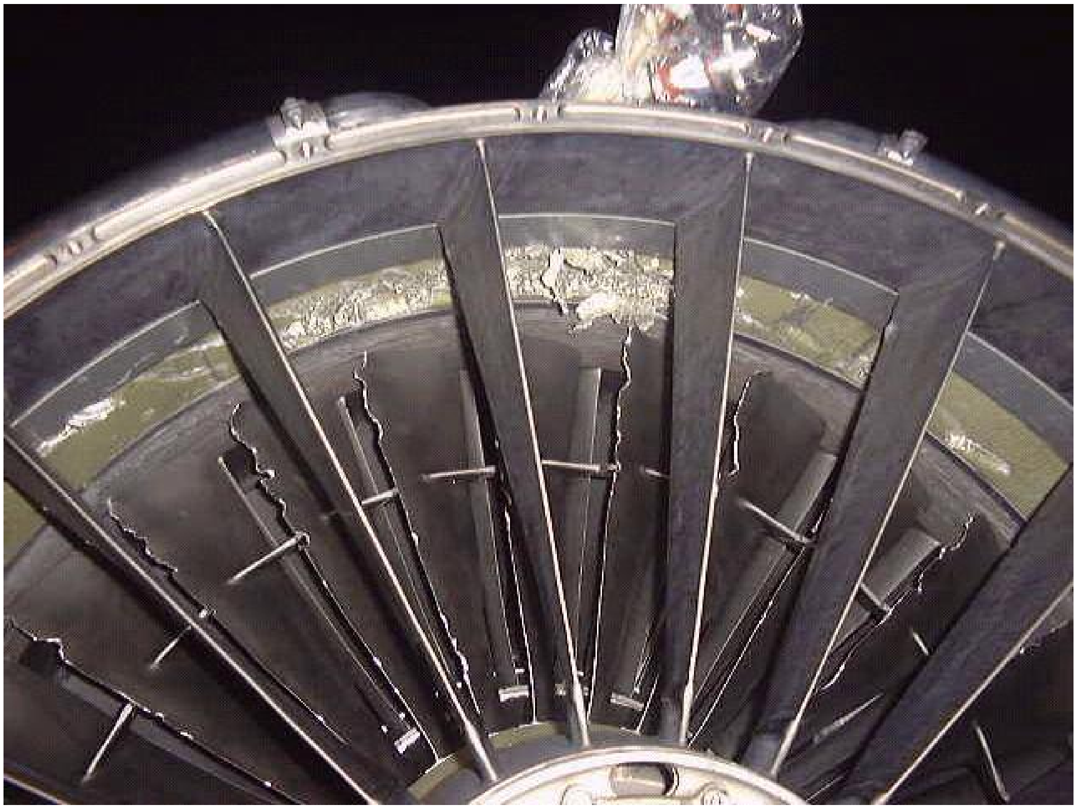

FIGURE 5 Example of damage caused by a tool. (Courtesy of F.A.S.T.)

FIGURE 6 Example of damage caused by hard ice. (Courtesy of F.A.S.T.)

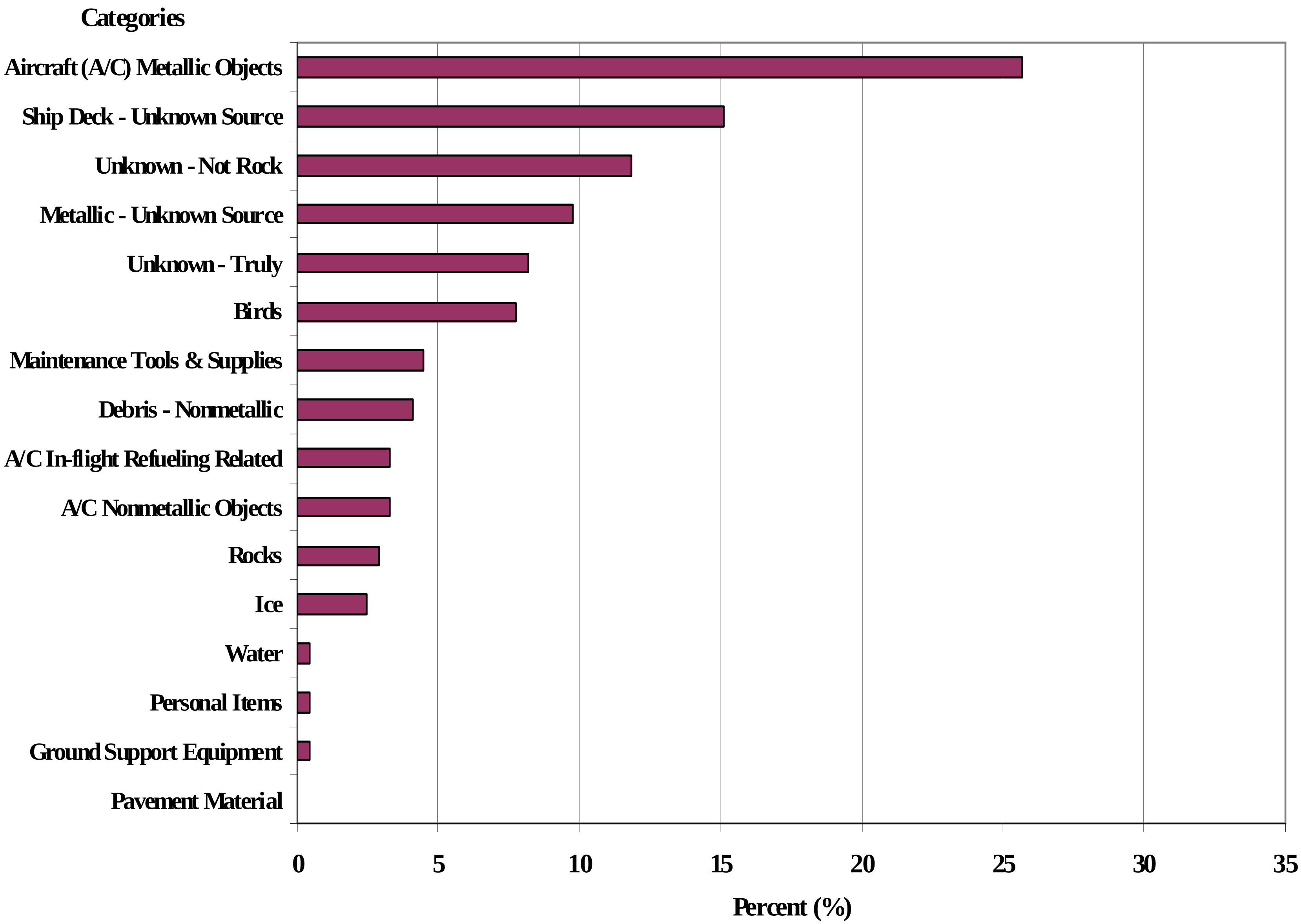

FIGURE 7 FOD incidents - All COMNAVAIRLANT data.

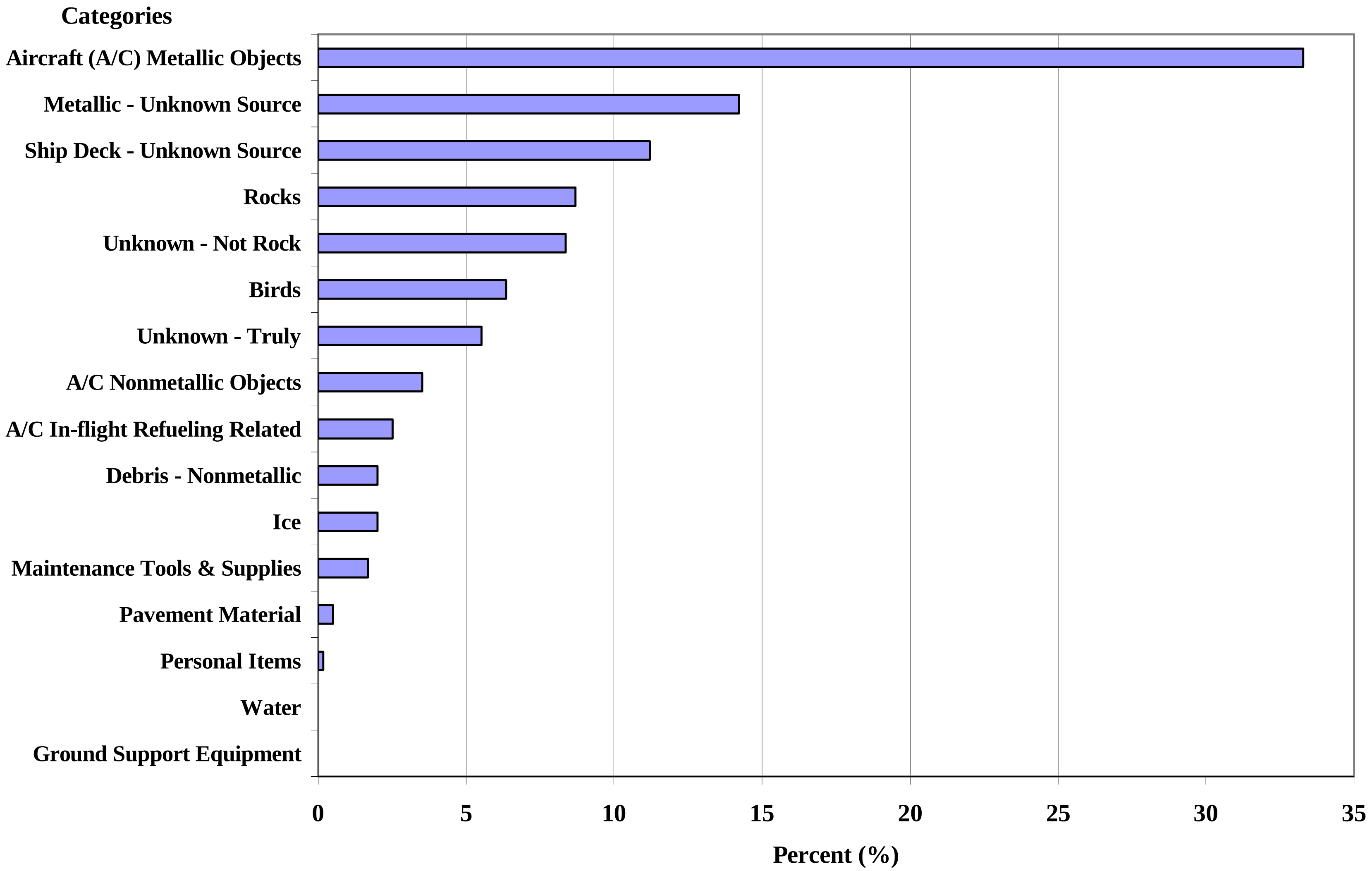

FIGURE 8 FOD incidents - All COMNAVAIRPAC data.

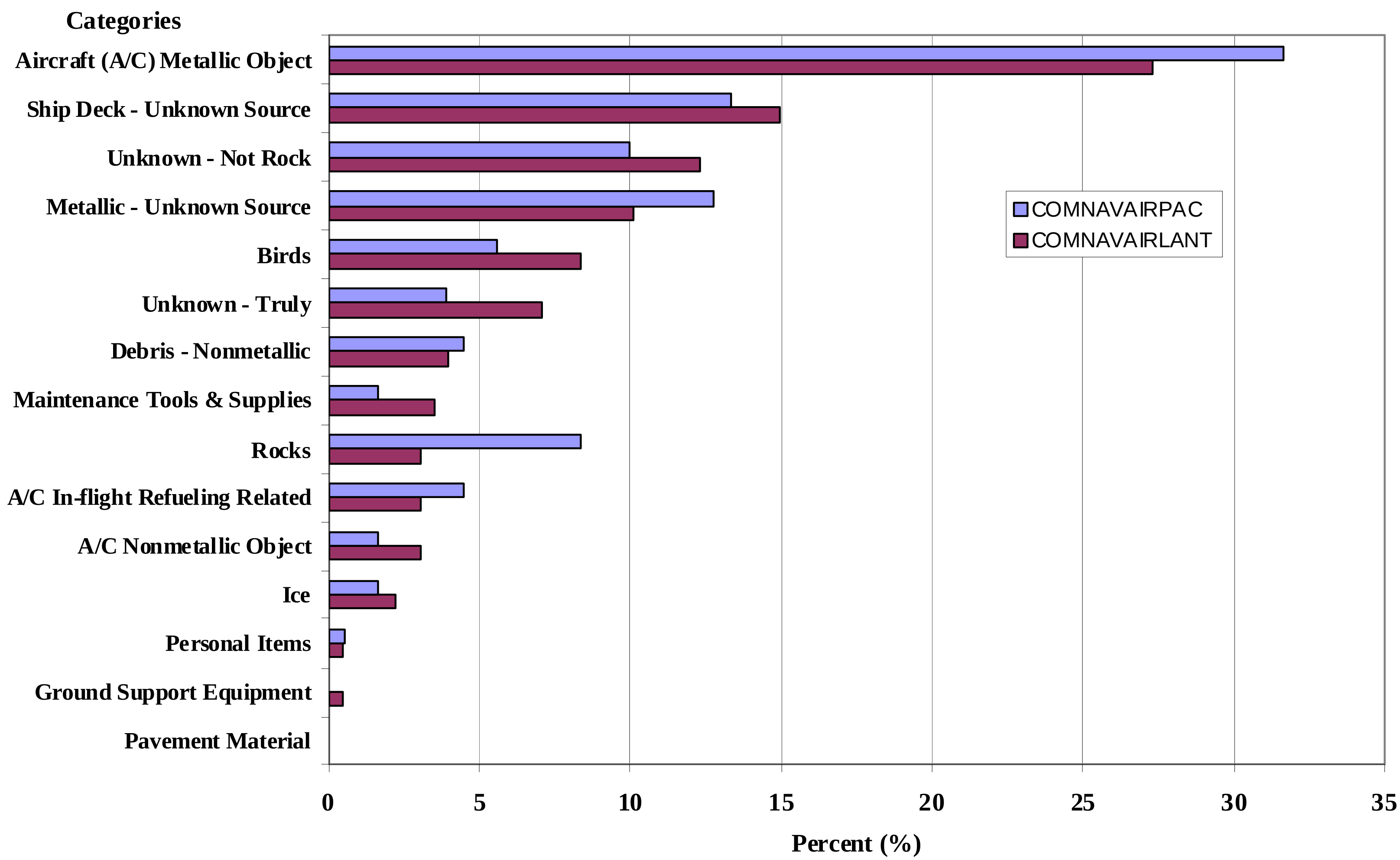

FIGURE 9 FOD incidents – COMNAVAIRLANT and COMNAVAIRPAC data for January 2002 through March 2003.

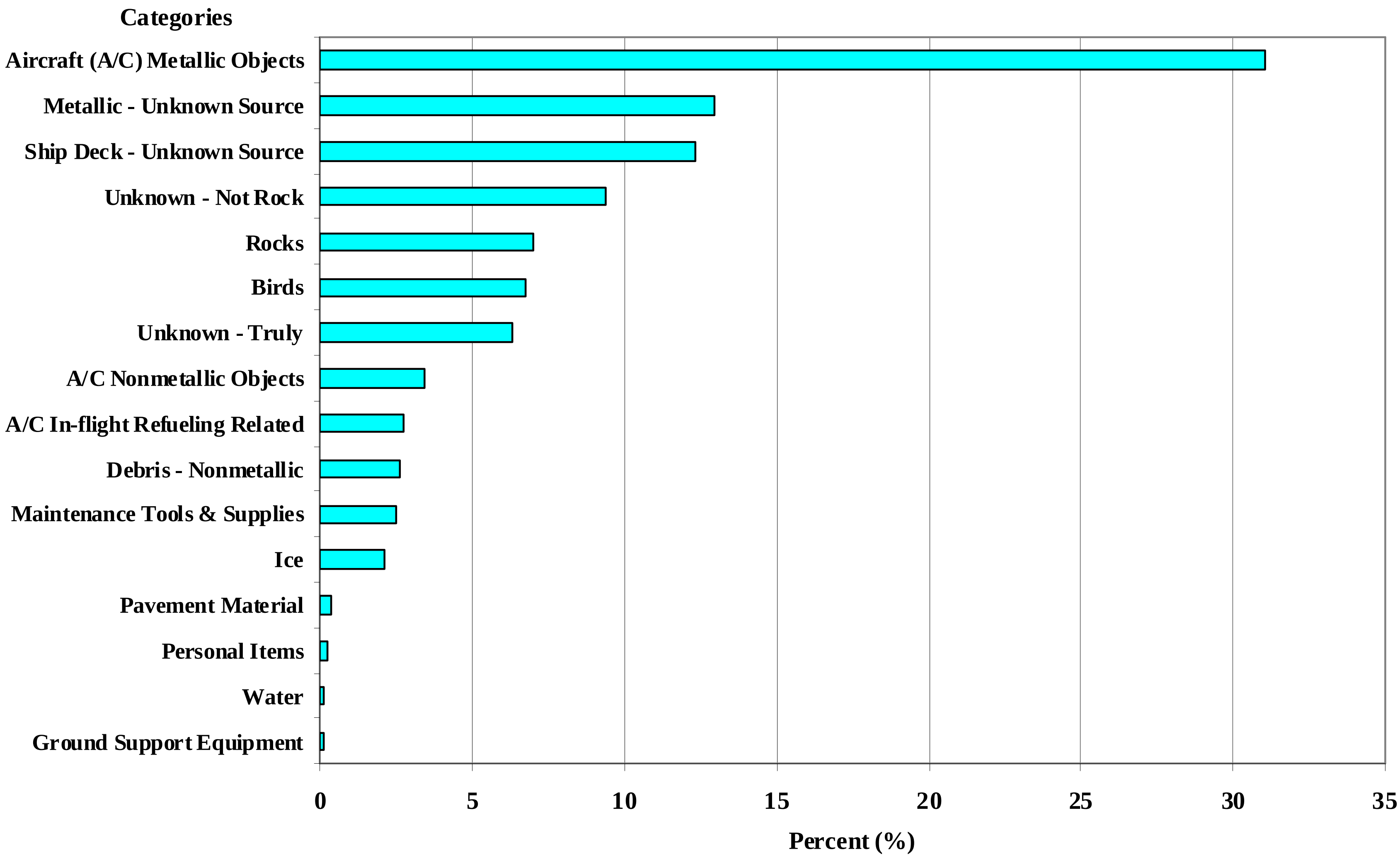

FIGURE 10 FOD incidents – all collected data combined.